# Laboratory tests of Riegl infrared laser distance sensors: range stability and water reflection characteristics

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# Executive Summary

This report contains results of Riegl laser tests conducted at NASA/GSFC's Wallops Flight Facility. All tests and information here pertain to the Riegl LD90-31000VHS-NOAA laser distance sensors (laser altimeters) flown on the NOAA/FRD's LongEZ for ocean wave observations. The main objectives of these tests were to:

- Document and characterize the short-term (minutes to hours) stability of the laser range measurements off fixed targets at ambient temperature.
- Characterize, under a controlled light wind environment, the laser measurement parameters for water surface reflections. This includes the response of the system vs. changing wind speed, up/down wave differences and vs. changes in incidence angle.
- Provide baseline sensitivity observations to assess potential of a scanning or fixed laser system to measure short wave directionality and/or parasitic capillary waves in the open ocean under light winds.

Findings are detailed in three different experiment sections to follow. Here we attempt to provide a concise summary pertaining to past and future field operation of these lasers on the NOAA aircraft and procurement of new ones.

**Re: Range Stability –**

Range accuracy of the units is generally within the specified +- 2cm limits but one can not assume that any of these three lasers is stable within those limits nor that the relative difference between units is stable. The range for any given unit off a static target does drift **slowly** with time (and we suspect temperature), mostly during a 30-90 minute initial warm-up period. We did not run the units through thermal cycling tests - our tests were performed at ambient laboratory temperatures.

Our recommendations:

- allow a minimum of 10-15 minute warm up before trusted data – [a question on any new procurement - what is the unit's warm-up behavior ?)]
- for ocean wave data processing needing cm accuracy one must have some sort of iterative leveling process for each data segment where the 3 lasers are self-leveled assuming range stability for that data segment's time period

**Re: short wave detection and characterization –**

Our tests suggest that these sensors would work well in a very simple wave specular reflection 'glint counting' mode that can detect or estimate - a) short wave onset, b) variation of short wave slope with changing wind speed, c) directionality of short waves, and very possibly, d) the modulation of the short waves along the underlying long waves. The laser would be pointed off 10-15° from vertical and simply measure the number of pulses returned with an amplitude of high enough level to assume that surface reflection had occurred. This could be a very effective tool for short wave and slick detection in the field. An azimuth scanning system would be best but even a fixed unit could provide valuable data.

**Re: surface penetration and in-water volume scattering -**

Field data has shown some cases where laser returns were captured when the surface was simply too smooth and we should have recorded dropouts. The recorded amplitude in these cases was much lower than for normal surface reflections. We were able to confirm with simple tests that most of these returns are likely due to the low-power in-water volume scatter that occurs right at the interface – most likely within the first sub-cm. This small power level is still enough for the laser units to detect and hence trigger a valid range measurement. We tested for the possibility that there was IR surface penetration that might lead to range error (walk or jitter). The data clearly indicate that the IR laser signal can penetrate and range off high reflectivity targets as low as 0.6 m below the surface. However, we conclude such targets are absent in the field and therefore this effect is unlikely to exist within our dataset.

# Laboratory tests of Riegl infrared laser distance sensors: Range stability and water reflections under light wind conditions

## Project Outline

1. Introduction
    1. Objectives
        i. Document and characterize the temporal (minute-to-hour) range stability of the laser
        ii. Characterize, under a controlled light wind environment, the parameters measured by the Riegl Infrared laser altimeter: range, amplitude, number of pulses returned.
        iii. Provide recommendation on optimal 2 kHz laser configuration for light wind data collection
        iv. Provide baseline sensitivity assessment of the potential for a scanning (or fixed) laser altimeter to detect short-wave onset and short wave directionality via the 'counting' of specular reflections versus view angle, wind speed, etc…

2. Motivation : low-altitude aircraft applications
3. Specific questions derived from past laser field data
    1. Cm-level range drift among the three lasers
    2. Surface reflections under light winds; dropouts and surface vs. volume scattering
    3. List of questions for laboratory investigation

4. General laser information and software
5. Experiment 1: Range stability
6. Experiment 2: Wave tank tests of the lasers under light wind conditions
7. Experiment 3: Water surface penetration at 903 nm using the Riegl IR lasers

## 1 Introduction

This report contains results of Riegl laser tests conducted at NASA/GSFC's Wallops Flight Facility. Most of the work was performed in July 2000. All tests and information here pertain to the Riegl LD90-31000VHS-NOAA laser distance sensors (laser altimeters) flown on the NOAA/FRD's LongEZ for ocean wave observations. The main objectives of these tests were to:

- Document and characterize the short-term (minutes to hours) stability of the laser range measurements off fixed targets at ambient temperature.
- Characterize, under a controlled light wind environment, the laser measurement parameters for water surface reflections. This includes the response of the system vs. changing wind speed, up/down wave differences and vs. changes in incidence angle.
- Provide baseline sensitivity observations to assess potential of a scanning or fixed laser system to measure short wave directionality and/or parasitic capillary waves in the open ocean under light winds.

## 2 Motivation – Low-altitude aircraft applications

NOAA operates a specialized experimental aircraft called a LongEZ to study near-surface atmospheric properties such as turbulence and air quality. (See http://www.noaa.inel.gov/frd/Capabilities/LongEZ) Recently NASA joined with NOAA and researchers from Oregon State University and the National Center for Atmospheric Research (NCAR) to instrument the aircraft for air-sea interaction measurements over the coastal ocean. A unique feature of this platform is its low altitude flight 'envelope' – the aircraft is routinely flown at altitudes as low as 30 feet above the ocean. This low level sampling permits the measurement of near-surface wind speeds and other properties that are of great interest to marine weather forecasters and climate study researchers. The low level platform also permits the use of low power ocean surface remote sensors to measure properties of the surface such as sea temperature, surface wave elevation and slope and small-scale wavelet roughness. The last parameter mentioned is of great interest for satellite applications as the ocean radar and radiometer systems used in space are basically built to measure the variability of these small scale waves over the globe – and to tie their signature to changes in the near-surface wind field.

One key surface measurement sensor on the LongEZ is a precise laser altimeter for measuring the range between the aircraft and the ocean surface with reported centimeter accuracy and precision. There are three identical units operating simultaneously on the aircraft. One objective of these measurements is to provide the surface elevation, or wave profile, as the aircraft translates over the ocean surface at approximately 50 m/s. Laser range data is collected at 50 Hz and so provides a range (elevation) measurement every 1 m along the flight track. This occurs for all three lasers. A second objective makes use of the three simultaneous range measurements to obtain directly a measure of the surface slope defined by the three laser points on the surface as shown in the figure. The quality of these range measurements, their relative stability and fidelity, ultimately, translate to the success or failure in deriving surface wave slope and elevation properties needed for the various studies being performed by the LongEZ.

**3 Specific questions derived from past laser field data**

### *3.1 Time/Temperature dependent cm range drift*

Initial study of the data from these sensors indicates that the range noise from the sensors is quite low (< 1 cm) and that the surface return is generally captured except under very light wind conditions. However, field data indicate that the absolute range measurement accuracy of the lasers is not static. Attempts to 'level' the aircraft over smooth inland water using the three lasers in an assumed fixed geometry leads us to suspect that the lasers' absolute range measurements can drift from day to day and hour to hour at the 1 to 2 cm level. We suspect that each laser's drift is independent of the others and could be temperature related. This level of drift is well within the specifications of the unit but does lead to problems. The basic problem that arises from this issue is the introduction of systematic error into our estimate of the instantaneous slope that makes use of the three laser range values on a 50 Hz basis. If the laser's drift together in the same manner this problem may go away – but for the time being we have been assuming in processing that the laser's are hard-mounted to the aircraft with zero cm range drift. This assumption needs modification and subsequent validation.

A following study addresses several remaining issues related to the laser surface range measurement and the general stability of the laser's range measurement. First, we wish to characterize an apparent time-dependent drift in the absolute range measurement (i.e. the accuracy). A 2-3 cm drift appears to occur within the first hour of operation and we need to document this and see if - 1) the drift is nearly the same for all three sensors; 2) if the drift is correlated with some measurable such as unit temperature; 3) some reasonable accounting for the drift can be performed in data post-processing.

### *3.2 Surface reflections under light winds; dropouts and surface vs. volume scattering*

A separate objective here is characterization of the laser's performance and capabilities under light wind conditions. This topic has to do with the reflection or scattering of infrared laser radiation off the ocean surface under very calm small ripple wave amplitude conditions, and the possibility of a subsurface volume scattering versus specular reflection. For the constantly moving aircraft the probability of getting a laser return to come back to the sensing unit off a calm surface is low. Yet, several intriguing features of the laser light wind data warrant further investigation. Our primary interest is documenting/exploiting the ability to see or trace the increase of surface 'fracturing' or wave generation as winds increase from calm to light wind values by accessing the number of recorded return pulses provided by the Riegl units. A second focus is understanding the optimal settings for obtaining the maximum number of range returns under light wind conditions to permit accurate surface elevation determination. Of secondary interest is the possibility of subsurface penetration of the infrared signals under very smooth conditions where the specular condition is seldom encountered under aircraft operations.

The laser altimeters aboard the LongEZ provide three parameters at a 50 Hz rate: range-to-surface (m), return amplitude (counts), number of return pulses (counts). In the first two cases, the value returned reflects the average of a possible total of 38 laser pulses that were transmitted by the sensor towards the surface. The final parameter provides an count of how many pulses came back to the sensor with a sufficient energy level to trigger a range measurement.

Under light wind conditions, (defined here as less than 3 m/s, or six knots) the surface generally becomes quite smooth with a typical absence of waves having length less than 5 cm. The laser beam's footprint on the surface from an altitude of 15 m is roughly a cm in diameter. Assuming the IR radiation reflects off the ocean one would expect that the probability of getting a surface reflection sent back to the laser would require some surface segment within that cm beam to be directly parallel to the laser's reference plane. At light winds, the probability of this should go down dramatically when combining the smooth surface with changing laser reference positions due to aircraft motion. We do find this to be the case. At winds above 4-5 m/s, we typically receive all 38 pulses. For light winds this number can go down to zero and is typically as low as 5-10. However, there is an additional piece of information found in the amplitude data. Laser average amplitude values typically vary from 10 to 150. The distribution of these values seems to indicate a bi-modal character (see next example data section) that indicates a two differing scattering processes – the high level return being specular and the low level return being an initial in-water volume reflection that is diffuse. This has been tentatively verified by some simple tests in the laboratory. It is also possible that we will receive range values off the ocean's bottom for data taken over shallow water under calm conditions.

### 3.2.1 Example light wind data from the SHOWEX program

The following data come from the Shoaling Waves Experiment (SHOWEX) and were collected 20 November 1999 from 14:08.35 – 14:33.35 UTC. The extended LongEZ flight track ran from near the coast of North Carolina on a southeast heading towards the Gulf Stream. Wind conditions ran from light to visibly very calm with slick surface patchiness reported by the pilot. The three figures provided here attempt to encapsulate different looks at the laser's light wind data collected during this leg. Where only data from a single laser (designated #0 here) are shown the other two lasers on the aircraft provided similar results.

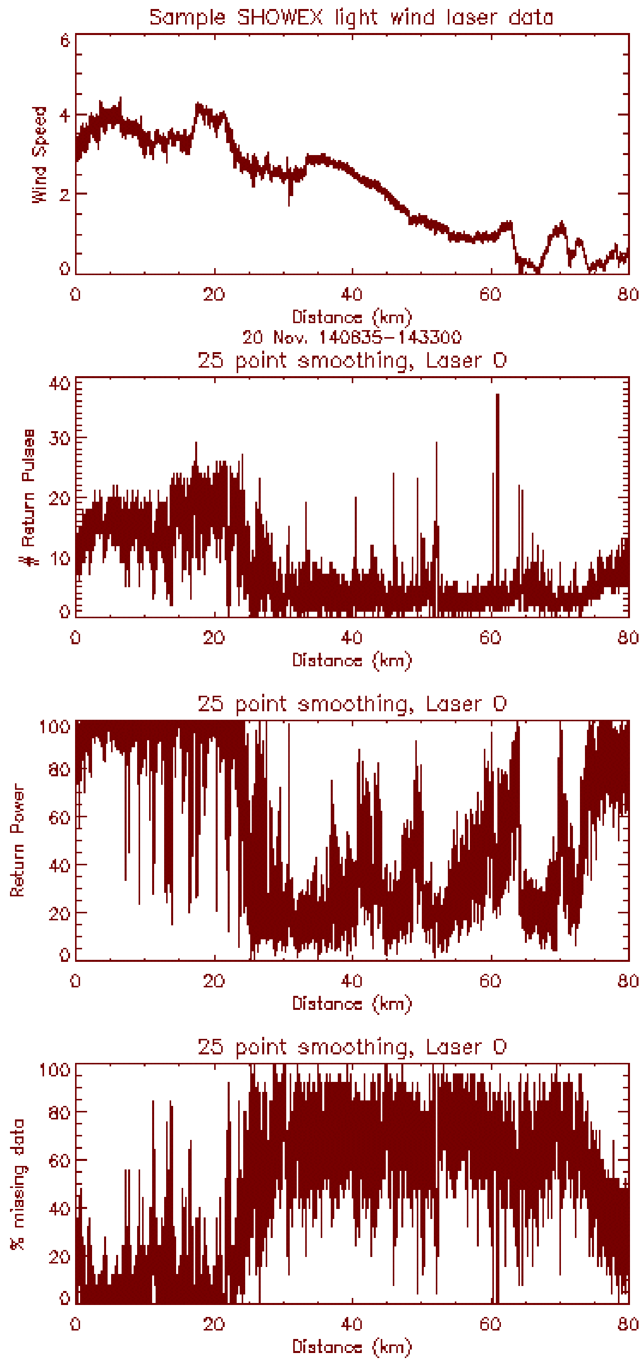



**Figure 1** shows data along the flight track, aircraft wind speed, laser # of returns (out of 38 possible pulses), the avg. return power for the measured pulses, and the average number of missing range measurements. Recall that each laser measurement represents the average of up to 38 laser pulses sent to the ocean surface. The power can vary from 0 to 256 counts. Also, note that on the figure the bottom three variables are shown as the result of a running 25-point average to clean up the display.

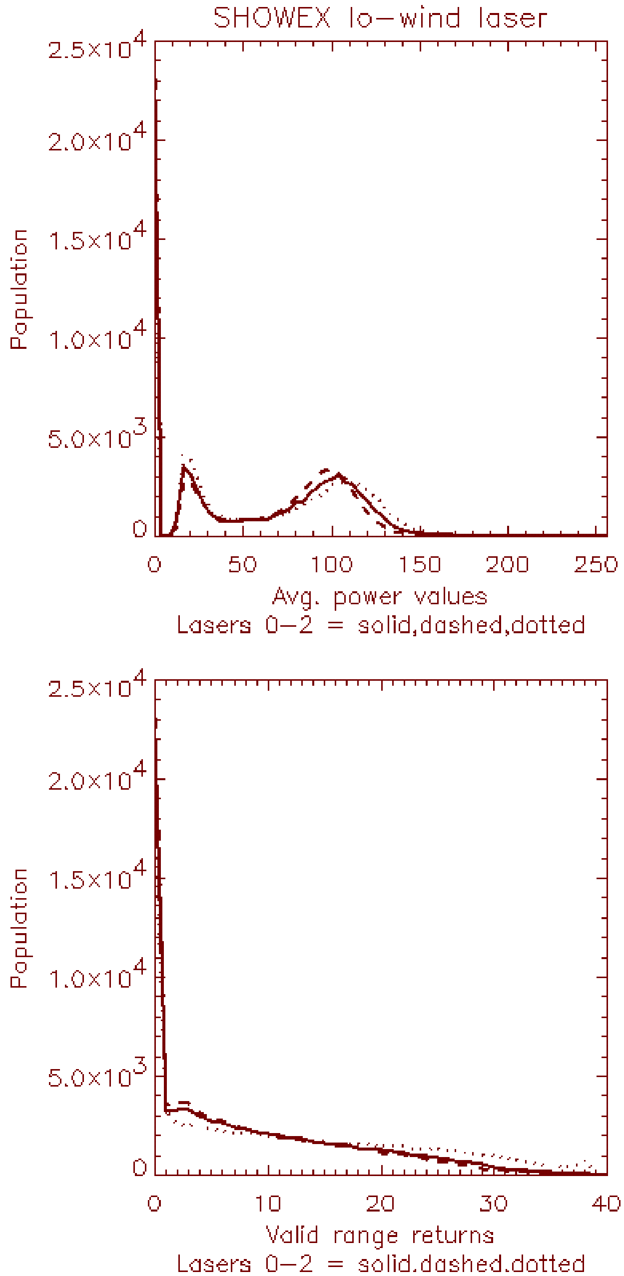



**Figure 2** shows the histogram of the amplitude and number of returns for the 38 pulses sent out in a given measurement sequence. All three laser data sets are shown. It is obvious that this was a light wind case for a large part of these calm surface data in that the most likely case was that we received no returns. From the number of returns one can see that there is then a continuum of values out to the optimal value of 38. The power shows an interesting bimodal distribution (aside from the large sampling at 0, i.e. a dropout condition). These two preferred values are about 10-15 and then about 100. These two 'modes' indicate the levels for diffuse and specular backscatter, respectively. Also, note that all three lasers have a similar spread of power and return values with the middle pod laser having the best number of returns and highest overall power.

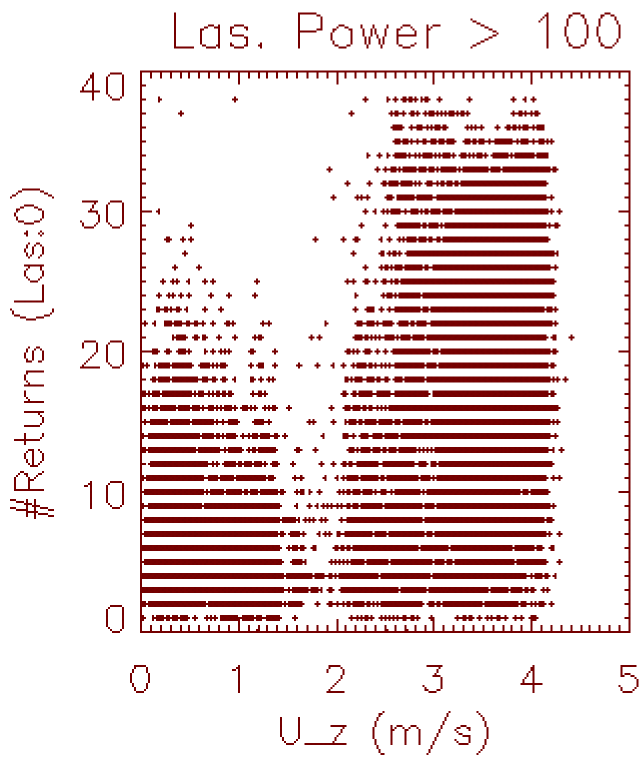



**Figure 3** indicates a simple attempt to plot the amplitude thresholded 'specular' returns (out of 38 total) versus wind speed. That is, this is a crude attempt to foresee what may be obtainable if we filtered out (in real-time) the diffuse, low power returns via the amplitude window on the Riegl sensors. As one can see, there is some sense that the number of measured returns did increase steeply after some critical wind speed of about 2.5 m/s. This accords well with past observations by Wu, Donelan, Plant and others will be the objective for laboratory tests later in this report.

*3.3 List of questions for laboratory investigation*

The issues raised above along with the need for high fidelity surface elevation and small-scale wave property measurements under the CBLAST light wind program leave us with numerous open questions that may be of interest for processing of past and collection of future data using the Riegl units. The following is a partial list in no particular order.

- Is there cm level range walk versus time and temperature?
- Is there range walk (essentially sub-surface (longer range) returns) due to competition between specular and in-volume reflections?
- Can we mimic the laser's known behavior for light wind conditions under wave tank conditions? (e.g. a high drop-out rate, diffuse and specular returns as shown in our example data from SHOWEX)
- Can we gate out diffuse vs. specular returns using control of the Riegl's amplitude window settings? When should this be considered?
- Does the number of specular returns vary with different wind and wave conditions, versus up/downwind look, versus viewing incidence angle?
- Does the diffuse number vary? (These two should be addressed by tests where the amplitude is gated)
- What is the limit to the depth of water that we are able to see down into when a fairly highly reflective surface is placed under the water?
- What different configurations (paddle vs. wind vs. fetch) can we potentially use in the wave tank to simulate light wind conditions on the open ocean?

## 4 **General laser information and software**

Three Riegl Laser Measurement Systems LD90-3100VHS –NOAA are used in the LongEZ aircraft and these same three units were used in the experiments described throughout this report. #1 (port)= SN 9990563; #2(pod) = SN 9991975; #3(starboard) = SN 9990562. This section documents some of the basics for these sensors. The sensor is a 903 nm infrared laser range finder with a Class 3B rating. They are not eyesafe and proper use of protective eyewear and safety procedures were observed in all tests. Overall we have found that the lasers exhibit similar ranging characteristics but do measure distinctly differing amplitude levels for a given target.

### *4.1 Laser footprint @ 12.5 m*

We measured the footprint of each of the lasers at a distance of 12.5 m. The illumination pattern is rectangular in shape, longest dimension is oriented along the long dimension of the optical aperture itself. The overall footprint is 1 3/8" by 2 3/8" ( 3.5 x 6 cm). There is a smaller central 'square' region of perhaps higher intensity. Our measurements were performed by tracing the beam while viewing through an IR finder and are good to 1/8". All three lasers were measured and we find that they agree to within our limits.

For the aircraft this means that we are about 3.5 cm along track by 6 cm across track for any given pulse.

### *4.2 Laser operation*

The unit is run in the field in a special high speed mode (hardware set via a jumper on the I/O connector) per NOAA's specification. The manual provides detail. One key point is that this mode provides a custom data stream that contains the number returned out of the pre-specified N pulses sent out during each range measurement interval. The units are controlled and polled for data over an RS-232 interface. In the field they are triggered at 50 Hz using a hardware generated trigger pulse. The nominal number of pulses to collect is N=38 for each 20 ms (1/50 Hz) measurement period.

In the laboratory we are doing a couple things different than in the field. First, we are collecting the wavetank data using both N=1 and N=38 settings. The N=1 setting captures information on **every pulse**. This allows us to cleanly assess the amplitude and range of every return to measure the power and range statistics. In particular we can see the range of power returns associated with specular returns – and see what the N=38 mode loses in terms of information by averaging all amplitude measurements together (see the SHOWEX example above).

### 4.3 Canned Software from Riegl

For the range stability tests at ambient etc.. we made use of the Windows software provided by Riegl to communicate with the unit via a laptop. The only command (aside from negotiating the serial handshake) needed is that one must go into the sensor settings area and set the trigger to free running. The main limitation to this software is that it does not handle the high speed mode and thus it does not have access to the number of return pulses. However, it does display/provide range and amplitude data. The RS232 is run at 19 kb.

### 4.4 In-house C Software for LINUX laptop using High Speed Mode

R. Mitchell developed a simple (non-GUI) custom program (and subroutines) to configure the sensor and collect data. Our main goal in the wavetank tests was to collect single pulse (N=1) data from the unit and thus 'number to average' is one of the selectable parameters. This software is written for the high speed mode at the 115 kb transfer rate. With N=1 selected were able to poll the laser at a maximum rate of 400 Hz (though the laser's PRF is 2 kHz). This capture speed was more than adequate for our purposes. the source and executable are located in /gen/rows/longez/riegl/Software/mitchell and the primary code for fine-tuning the program is main.c.

## 5 Experiment 1: Range Stability

### *5.1 Set-up*

In order to determine the range stability of the laser, the unit was set up on the bench to run for an extended period. The laser was placed about 2 meters from a white sheet of paper used as a target. Tests were conducted at room temperature and with varied starting temperatures. The temperature of the unit was decreased and increased by placing the unit in a refrigerator and in a car window wrapped in black material. In each test, the unit was allowed to run until the output became stable. These periods ranged from 75 minutes to two hours. During these periods, the data was recorded by hand (distance and amplitude) into a log.

During these tests, the lasers were connected to an Everex laptop (NASA serial #1817504) via a cable and the software provided by Riegl was used to view the data. At the time this report was finished, the software was still installed on this computer. The software operates in Microsoft Windows and is simple to use. The lasers were powered by a DC power supply also via a cable and run in low speed mode. Later tests were run to log the data to computer with the laser in high speed mode. No difference is expected in the output between these modes as the speed merely indicates the data transfer rate – not internal laser operation.

We note that the specification for the Riegl units in terms of absolute accuracy is +-2 cm (+- 5 cm worst case). This figure is given in the front of the LD90-3100VHS-NOAA manual. Also note that 1.3.5 of the manual suggests that the maximum warm up time should be 20 minutes to guarantee full accuracy.

### *5.2 Test Results*

Three sets of tests were conducted. The first set compared the stability of each of the three lasers at room temperature (shown in **Figures 4-6**) The second compared the stability of laser #2 at varied temperatures. Tests were run with laser #2 beginning at room temperature; after being cooled in a refrigerator for a significant period; and after being warmed to 110°F for a significant period (shown in **Figures 7-9**). The Microsoft Excel data files from which these graphs were derived are in the ROWS directory located at G:\longez\Riegl\Range_Stability. In the same location, there is a Microsoft Word file, named Experiments_contents.doc. It lists date, duration, laser used and temperature conditions for each of the first two test segments.

In Figures 4-9 to follow the distances are all relative to the given bench tests and thus do not provide data for absolute intercomparison. That data was generated a test set three to be described below.

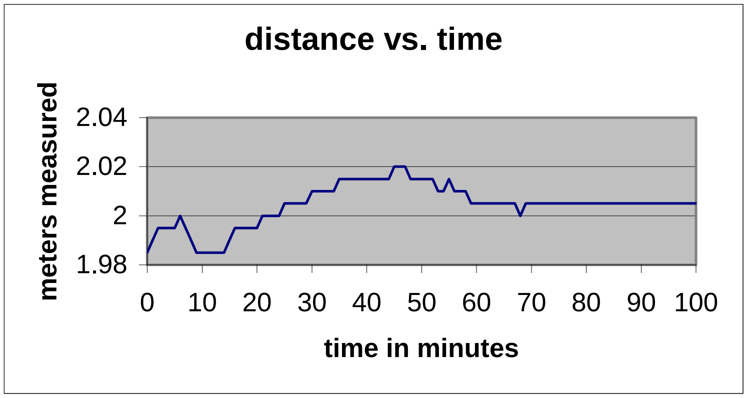



**Figure 4** - Data show the range that laser #2 displayed over a period of 100 minutes under normal room conditions. The range displayed steeply increased and then, decreased over the first ten minutes. In the next hour, the display mimicked this behavior much more gradually. In the final 30 to 40 minutes of the test, the range settled.

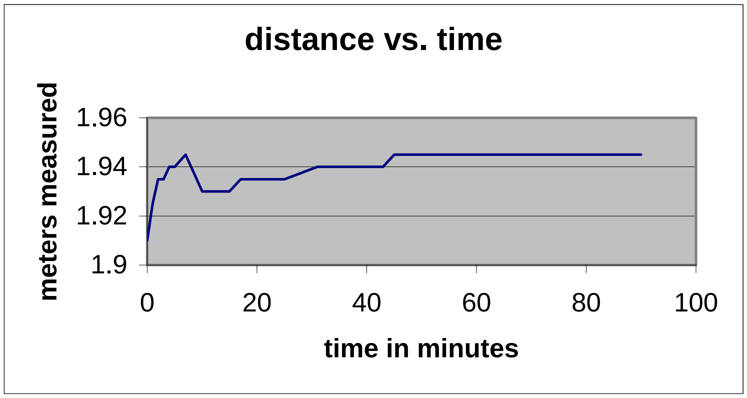



**Figure 5** - Data show the range that laser #1 displayed over a period of 90 minutes under normal room conditions. During the initial ten minutes laser #1 behaved similarly to laser #2, it steeply increased and decreased. After the initial ten minutes, laser #1 was increased gradually before settling about 45 minutes after the test began.

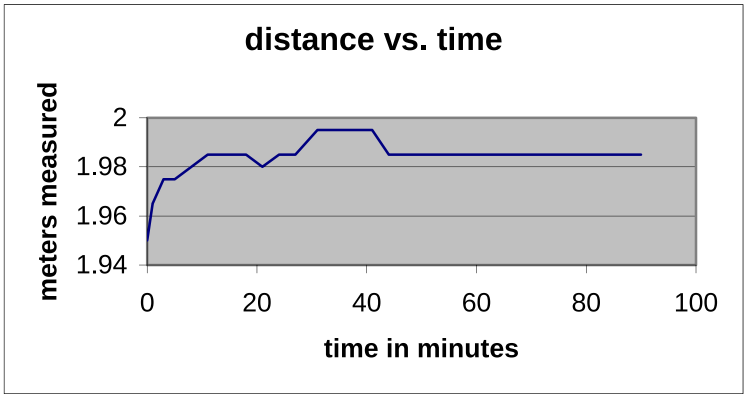



**Figure 6** - Data show the range that laser #3 displayed over a period of 90 minutes under normal room conditions. During the first 40 minutes, laser #3 range increased steadily. After this time, the distance displayed decreased slightly and settled about 50 minutes from the start of the test.

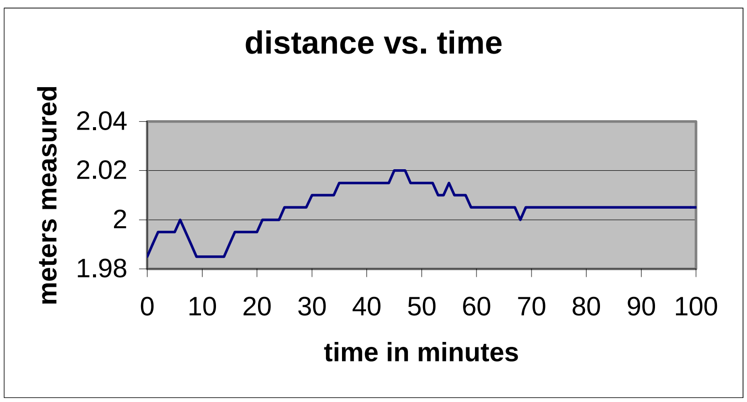



**Figure 7** - Data show the range that laser #2 displayed over a period of 100 minutes under normal room conditions. The range displayed steeply increased and then, decreased over the first ten minutes. In the next hour, the display mimicked this behavior much more gradually. In the final 30 to 40 minutes of the test, the display settled.

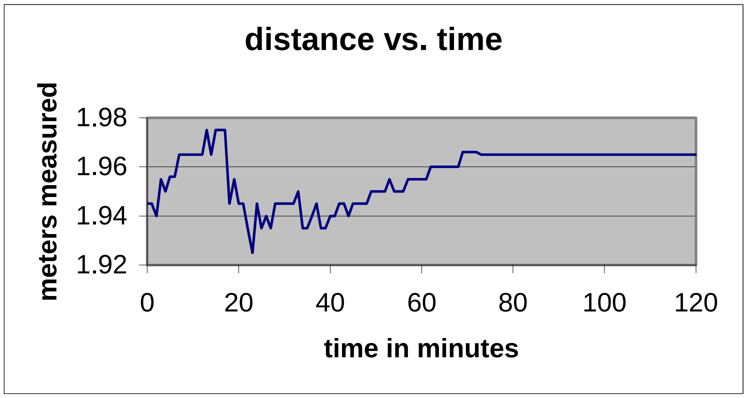



Figure 8 - Data show the displayed range of laser #2 for a period of 2 hours after it had been chilled (~ 40° F) . Over the first 20 minutes the range increased and decreased steeply. In the next 60 minutes, the range gradually increased. About 80 minutes after the start of the test the range value stabalized.

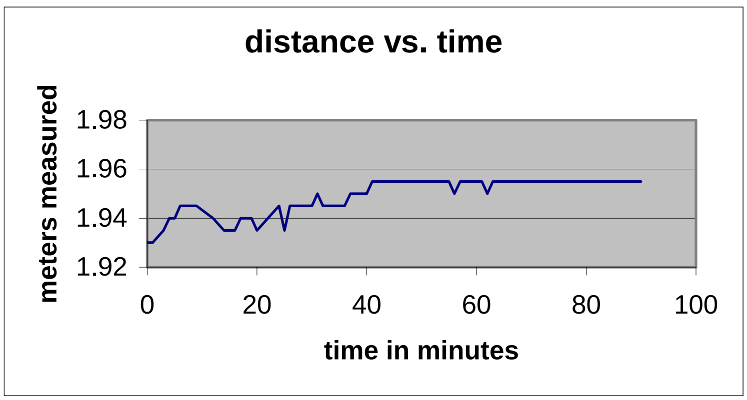



**Figure 9** - Data show the displayed range of laser #3 for a period of 90 minutes after it had been heated to +110 F. In the first approximately 15 minutes, the display increased and decreased slightly and then rose and fell slightly with an overall upward motion before settling after approximately 45 minutes from the start.

### *5.3 Side-by-Side Test – Absolute Range - Results*

After initial tests, two questions remained a bit open. How does each laser's time stabilization compare with the others ( at ambient room temp. and varied temperature )? and Is a given laser range-stable after a given time for the remainder of the data collection period –i.e. does the range value drift after fully-warmed up? To answer these a bit more completely we revisited the tests above, now using the software developed to log the data to the laptop.

The first tests here were simply to set the lasers up on a fixed distance paper target and intercompare their absolute range drift versus time at room temperature. Each laser was run for two hours and with the pulse average set to the N=38 field value. Results for the three are shown in Figure 10. As one can see in panel a, the overall time response – overshoot followed by a slower stabilizing zone is evident for all three lasers. Panel b of Fig. 10 shows the relative difference of #3 and #1 from #2. It appears that the bounds of the difference variation is about +- 1 cm after an initiially erratic 10-15 minutes settling time. The units do not settle into a stable absolute range after that time but the drifting appears to be at a very slow rate of less than 1 cm/hour or (0.16 cm/10 minutes). Lasers #2 and #3 appear to exhibit a similar drift response over the 2 hour period with laser #1 moving in an independent manner. The absolute differences are a bit difficult to determine as the lasers seem to stabilize in varied relative deltas. We report a best estimate that may be irrelevant if the units stabilize somehow arbitrarily within the +-2 cm region.

**Absolute range differences between LongEZ 2 kHz Lasers, Sept., 2000 after stabilization**

| | | |
|---|---|---|
| Laser 1 – Laser 2 | = | -3.0 cm (+- 2.0 cm) (see Figs 10,11,12) |
| Laser 3 – Laser 2 | = | 2.5 cm (+- 1.0 cm) |

For reference purposes – we report that the range value standard deviations for all three lasers off this diffuse target are very consistent - [0.0019, 0.0021, 0.0018] for laser's 1,2, and 3 respectively. Power levels off white paper are [138,154,126] respectively.

Figure 11 provides longer term drift data for laser #1. These data were taken to assess how much the lasers move with time and if they ever really stabilize. Referring to Figure10 at time of one to two hours one can see that this independent data set does repeat the results of Figure 10 in long term trend. Overall it is clear that the laser can move a bit with time but this unit is generally to +- 0.025 cm level over a 15 hour period. The ambient temperature swings over this period were likely of the order of less than 10-15 deg. as the window to this area was left open. We suspect that the slight increase in range at time=5 hours is due to a general outside temp. drop at that time.

### 5.4 *Conclusions with respect to range stability*

We conclude:

- That the laser's are within the specified absolute accuracy of +- 2cm.
- That the laser ranges measured off a static target will move at the level of +- 2 cm, most dramatically within the first 10-20 minutes but they all do not stabilize completely under static ambient temperature conditions.
- After warm-up, a laser's absolute stability appears to be well within a +- 0.5 cm – our best estimate for laser #1 is +- 0.25 cm; for laser #2 comparable or less.
- Temperature effects do not – under simple tests – appear to be a large issue but might very likely be the cause of the small slow drifts (sub-cm) with time.

- **One can not assume that the laser's have a stable difference between their absolute range measurements at the day to day or hour to hour interval.**
- The time rate of change in the absolute range 'error' is quite small and so leveling between lasers over even a ten-to-twenty minute period can be done under a zero-drift assumption.
- For field experiments a laser warm-up period of 20-30 minutes would help to stabilize range difference determination – but even ten minutes would help greatly (as is the recommendation from Riegl). This has usually been the case to date.
- There is probably not a justifiable need for a thermal chamber test of these devices with respect to this range stability issue – but still an open question.

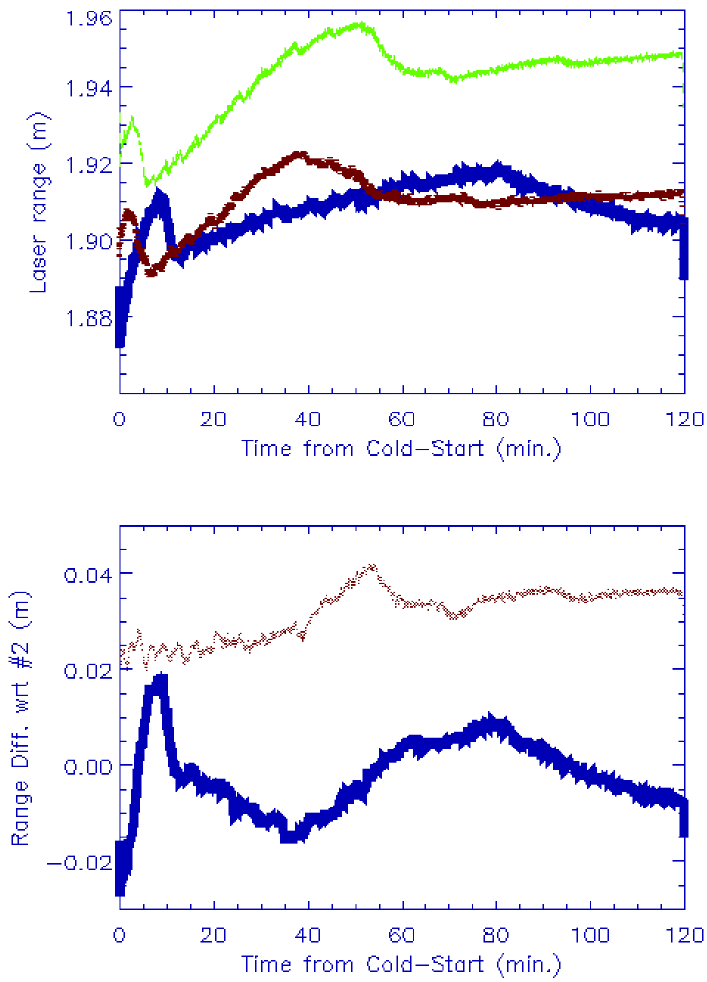



**Figure 10 – (a)** Range measurement off a static white target versus elapsed time from a cold start for all three laser units. The thickest trace (blue) is for #1, the thinnest trace (green) is the #3. The 50 Hz data have been smoothed considerably. **(b)** Bottom panel provides the relative difference between #1 and #2 (thick trace) and #3 and #2 (thin red trace). Note that in both cases the relative error versus time varies less than 1 cm after the 20-30 min. warm-up period.

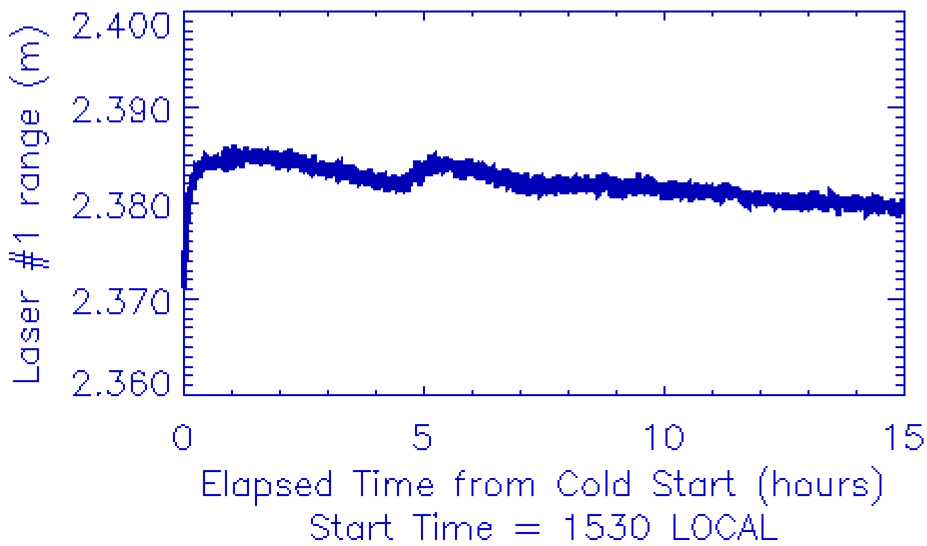



**Figure 11 –** Range measurement off a static white target versus elapsed time from a cold start for laser #1. Note that the laser range varies less than 0.5 cm over the whole 15 hour period of this test. Also note that the cold-start indicated here was not truly a cold-start as the unit had been run within the last half hour before test start.

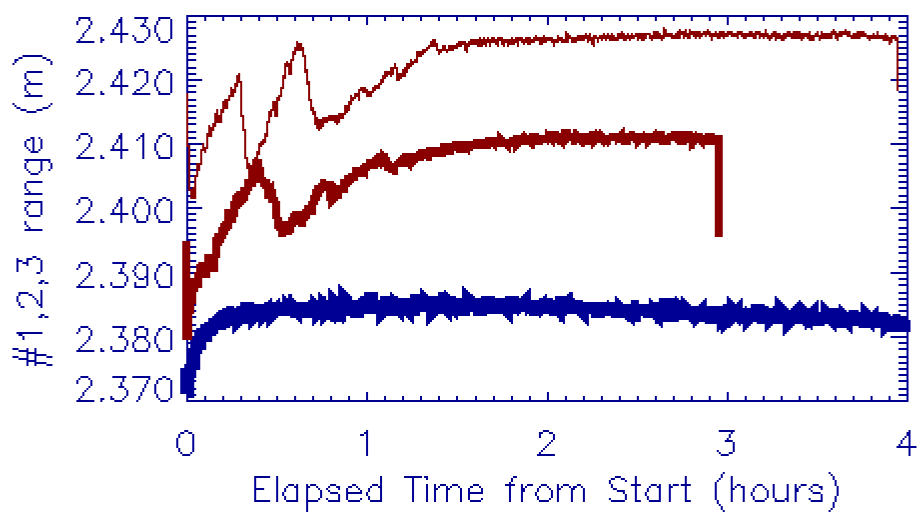



**Figure 12 –** Range measurement (N=38 pulses) off a static white target versus elapsed time from a cold start for lasers #1, 2 and 3 (thickest to thinnest trace, respectively). Note that each laser range stabilizes within about 90 minutes. Disregard the sharp discontinuities at the endpoints. The range differences between units for this case are not the same as for the case of Figure 10. Laser #1 data not from a cold start as noted in Figure 11.

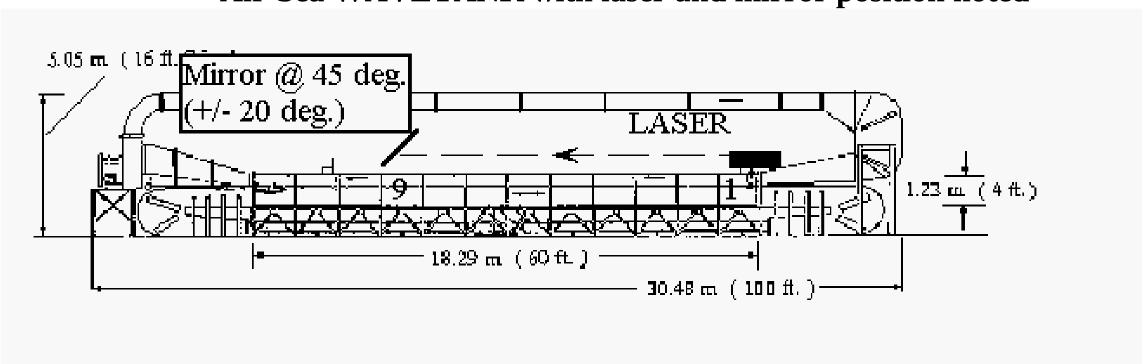
## 6 Experiment 2: Wave tank tests of IR laser under light winds

### *6.1 Set-up*

In attempt to characterize the properties of the water reflections measured by the Riegl Laser Measurement Systems LD90-3100VHS – NOAA used in the LongEZ aircraft, the laser labeled #2, was used to measure waves in the wind-wave tank at the Wallops Flight Facility (see http://airsea.wff.nasa.gov) with much assistance from S. Long. The laser data were stored and displayed by the software R. Mitchell designed expressly for this project. It was run on the Compaq Prosigna (NASA serial # 2038265) operating Linux. As for the range stability tests, cables connected the laser to the laptop and power supply, in this case the high speed mode jumper was engaged.

During the first set of tests in the wave tank, the laser labeled #2 was placed at the northern end of the wave tank (above panel 1) and was fired onto a mirror located 12.5 meters down the tank (above panel 9). The laser was able to reflect off the 6 " diameter mirror into the wave tank creating a total distance from the laser to the water in the wave tank of 13.1 meters.

**Air-Sea WAVETANK with laser and mirror position noted**




Waves were generated using eight different wind speeds, one being no wind. In addition, waves were generated using each of these wind speeds in conjunction with a paddle wave (900 mV, 1.25 Hz) creating 16 different wave conditions. Measurements were taken with the mirror angle at the specular point (~ 45°) and then plus and minus five and ten degrees from that point. The specular point was determined through trial and error to be the point when, with no waves, the laser range gave consistent surface ranges and high power levels. At each mirror angle and tank condition, data were run with Riegl averaging numbers of one and 38. Data from each of these tests can be found in the directory osb4:\gen\rows\longez\riegl\Wavetank. In this directory are sub directories listed by date. Also in this directory, there is a Microsoft Excel file named Master_wavetank.xls that lists each of the files taken by full name and indicates the wave condition created by the fan and paddle as well as mirror angle and averaging number.

S. Long provided wave wire surface elevation data and Pitot-derived wind profile data for each of test run conditions. The preliminary results of those data are given in Table 1.

**TABLE 1 – WaveTank Wind and Wave Data for test sets**

| Fan Speed | Paddle Wave (1.25Hz) | U_14.8 (m/s) | U_15.8 (m/s) | U_18.8 (m/s) | rms_Z (cm) | rms_slp |
|---|---|---|---|---|---|---|
| 0 | 1 | 0.0 | 1.77 | 0.90 | 0.480 | 4.276 |
| 9 | 0 | 0.0 | 1.13 | 2.383 | 0.028 | 0.355 |
| 9 | 1 | 0.25 | 1.28 | 2.33 | 0.434 | 4.264 |
| 11 | 0 | 0.68 | 2.33 | 2.87 | 0.098 | 1.839 |
| 11 | 1 | 0.93 | 2.17 | 2.97 | 0.373 | 3.730 |
| 13 | 0 | 2.14 | 3.13 | 3.54 | 0.154 | 2.920 |
| 13 | 1 | 1.91 | 3.00 | 3.58 | 0.385 | 4.097 |
| 15 | 0 | 2.96 | 3.77 | 4.14 | 0.231 | 4.175 |
| 15 | 1 | 3.08 | 3.86 | 4.28 | 0.498 | 5.810 |
| 20 | 0 | 4.92 | 5.52 | 5.73 | 0.413 | 6.453 |
| 20 | 1 | 5.05 | 5.61 | 5.80 | 0.669 | 7.468 |
| 25 | 0 | 6.56 | 7.09 | 7.22 | 0.553 | 8.084 |
| 25 | 1 | 6.56 | 7.07 | 7.24 | 0.686 | 7.547 |
| 30 | 0 | 8.03 | 8.55 | 8.73 | 0.780 | 10.657 |
| 30 | 1 | 8.08 | 8.57 | 8.73 | 0.954 | 9.736 |

The wind speed data of Table 1 are derived from altitudes above the surface of 14.8 to 18.8 cm. There were no visible small surface waves for the lowest fan speed (9) at our tank panel 9 location and so this was considered as the minimal light wind condition – however one can see that the highest Pitot is giving a reading of 2.3 m/s. Small waves were apparent at the fan setting of 11 and this turn on of short waves vs. wind speed does not appear to far off the predicted wave onset ranges reported recently by Donelan and others. With 1 m paddle wave introduced, the wavelets start earlier for a given wind speed and initially appear only along the crest of the waves.

Photographs were taken for each wave condition and their tabulation vs. photo number are listed in a table under the directory gen/rows/longez/riegl/photos. Two examples are provided below in Figures 12 and 13.

An immediate finding was that the laser beam size at 12.5 m was larger than anticipated (see section 4) and the laser illuminated a substantial portion of our mirror – with some probable stray radiation hitting the structure built to hold and adjust the mirror angle. The result was that in the absence of a strong water surface reflection the laser altimeter would range to the mirror distance even though the mirror angle was set to send most of the energy down at 45°. The amplitude of this 'mirror return' was much much lower than the surface specular return, 15-25 counts for the former and 160-180 for the latter. However, this low-level mirror return was higher than the initial in-water volume scatter (amplitude~ 10 counts) seen in the earlier laboratory tests (see section 7). The impact was that **we were not able to study volume vs. specular reflections in the wavetank.** The mirror returns were gated out of our study using the range (12.4 m) and power (< 30 counts) so that we were able to study the surface reflection data that was the main objective of our investigation.  Example data to explain the mirror return are shown in Figure 14 where histograms of the measured range and power (amplitude) data for every laser pulse (N=1 averaging) are tabulated.  The mirror returns lead to the bimodal distribution where erroneous range measurements from 12.4 to 13.0 m are due to this 'target' likely confusing the threshold power tracking circuit inside the laser.

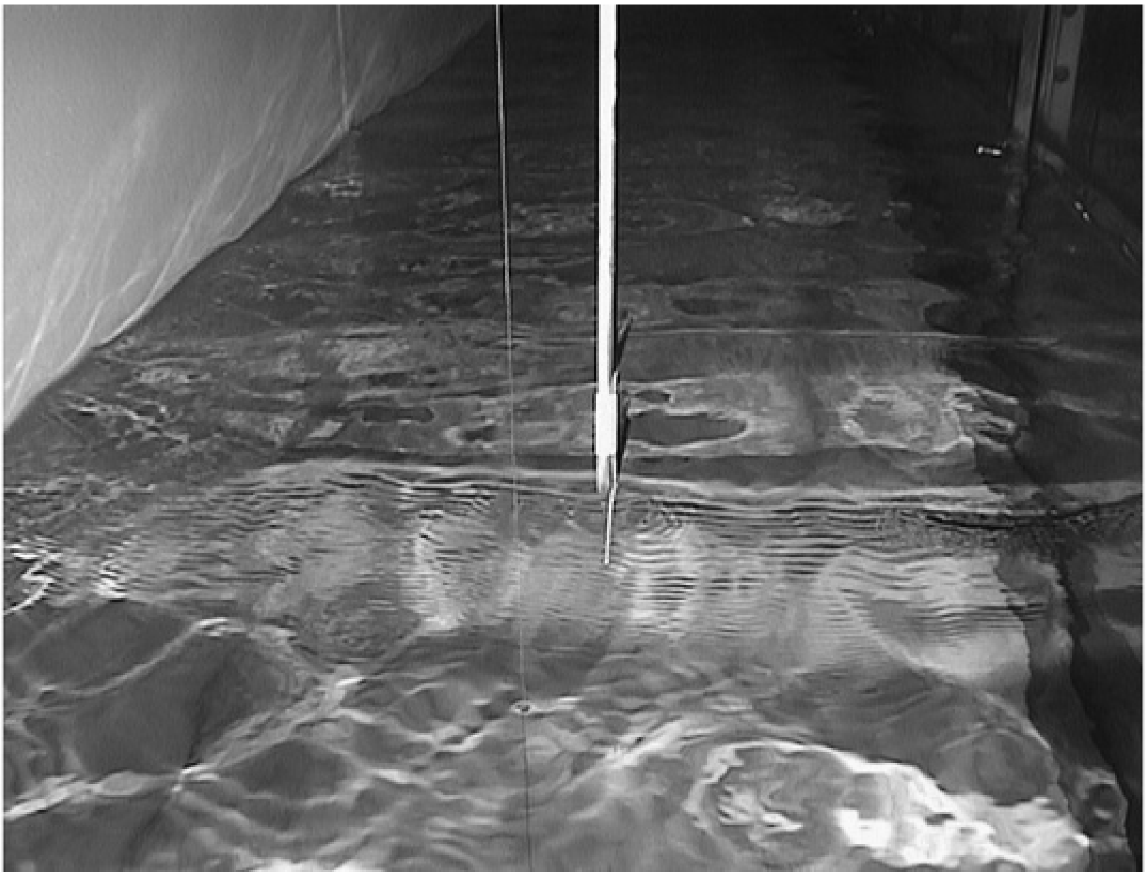


**Figure 12** - Digital photo of the wavetank surface under the laser tests for the initial onset wave condition of a paddle wave of 1 m and near surface winds of 2.3 m/s (fan speed of 9).  This is the most deterministic case of short waves riding on rise in the paddle wave.  Note that no short waves were evident for this wind setting when the paddle wave is removed.  The Pitot sensors are the wider probe in the tank's middle and the thin line to the left is the wave wire gauge used to measure the surface elevation.

**Figure 13** - Digital photo of the wavetank surface under the laser tests for the initial onset wave condition of no paddle wave and near surface wind speed of 2.9 m/s (fan speed of 11). This is the case of initial short waves generation due to wind alone. It took a bit of time for this situation to develop and stabilize at panel 9 ( ~ 12.5 m fetch). One can see the rhombic-like pattern recently noted by Caulliez et al. under light winds – but one does note that short waves are indeed present at the scale of cm.

### *6.1 Summary of Results*

The recorded tests provided laser data on conditions ranging from smooth, unbroken water to breaking waves and for laser viewing angles from 0, 5 and 10° from normal to the surface. Our objectives are spelled out in the earlier sections. The following figures provide the baseline results and examples. In general the tests provided much of the information we are seeking. The mirror contamination did negatively impact the work in two ways. First, it removed the possibility to assess the N=38 pulse data as we could not filter out the mirror from surface returns. This left us with using the N=-1 data which were fine for most our needs but did preclude exact replica of the field configuration. Second, we were unable to assess in-water volume scatter versus surface reflection. See section 7 for more on this. Otherwise, it was clear that the wavetank conditions – with the special boundary layers and low sea states – are not a direct proxy for the open-ocean. Therefore we use these data as a general tool to assess the laser performance but do not propose that field results will be identical.

Figures 14 and 15 provide some look at the raw data and serve to demonstrate what we will refer to as the specular ratio, **S** :

**S** = number_with_amplitude > 30 cts / total_number_surface_measurements

In this study we are most interested in the number of pulses that return back to the laser for a given sea surface condition. Under a specular scattering (ray tracing) assumption this should be a reflection from some surface facet that aligns with the laser's direct view angle and falls within the laser's 3.5 by 6 cm footprint. The highest specular return power that we measured off of smooth water was about 210 counts in amplitude (or power). As one can see from Figure 14 the power levels drop once the surface starts to fracture and wave develop. This is because only a portion of the facets within the laser footprint scatter the power back. So the distribution of power levels shown provide a sense of the range of individual power returns due to specular scatter down to the mirror limitation point. We note that in the field S could be readily determined by first gating the low-level amplitude setting of the sensor, currently set to 0, and then looking at the already recorded 'number of returns' that is typically 38 for present operations.

Figure 15 provides some raw time series data from fairly smooth light wind conditions where we only show those points that are surface returns. The mirror returns are filtered out using the range (above 13.0 m). These data comprise the 'total_number_surface_measurements ' denoted above. **S** is simply a measure of those cases of surface return above a power limit of 30 counts. As one can see, the case of valid laser returns from the surface is sporadic under light winds. Referring back to the example photos one can see periodic regions of small waves – these correspond to regions of specular laser return. The laser's response will vary with wind speed, wave slope, incidence angle, and up versus downwind orientation of the incidence angle. The initial data showing these responses are provided in Figures 16-22. We assume that stepper wave slopes are required to generate laser response for the 10 deg. view angles. Short cm-scale waves are generally the steepest and these waves are modulated along long waves and readily generated by wind gusts. Thus a in goal is to see how well the data at 5 and 10° incidence scatter versus changes in the wave(wind) climate. In the following figures and notes we do not dig into the modulation of the signal along the long wave slope nor the relation of the data to the recorded slope values.

We observe:

- A relative saturation, or insensitivity, of the 0° incidence specular ratio to changes in the wind speed (see Figs. 16 and 18).

- A much clearer correspondance between **S** and wind speed for the 5 and 10° angle data
- A clear 'turn on' of the specular reflection at about 2-3 m/s in wind speed for the 5 and 10° angle data (see Figs 20 and 21)**.** We assume this is the onset of small grav. -capillary waves.
- A general trend towards saturation of the specular ratio for the 10° data as one gets towards 8 m/s.
- The surface conditions clearly differ between the cases with and without the 1.25 Hz paddle wave. This is illustrated in Table 1 and Figures 18-21. Figure 19 is probably the most dramatic indicator.
- A rudimentary rendering of the 'glint count' versus incidence angle and wind speed along the lines of the slope PDF studies of Cox and Munk (1954) or Shaw and Churnside (1998) is given in Figure 17. We expect this would be more clearly generated in the field in the absence of mirror and wave tank condition impacts. But the basic fall-off with angle and skewness of up versus downwind is readily observed.

Preliminary conclusion:

Results obtained here will not translate directly to interpretation of past field results due to non-representative wave tank conditions and the fact that we use a N=38 average in the field that implicitly loses information on scattering variability. Nonetheless these data should be useful in understanding the causes of dropouts and general nature of the laser operation under light wind.

A laser system such as the Riegl could be set-up in a fixed or azimuth scan mode with a 10° incidence angle and used to - a) detect short wave onset, b) variation of short wave slope with changing wind speed, c) directionality of short waves, and very possibly, d) the modulation of the short waves along the underlying long waves. Such a system would not be used for high fidelity range work as dropouts would now be more common. Rather its main parameter of interest would be the % of valid returns out of the N sent in a given segment (now set to N=38). The one revision of current settings would be to change the amplitude low cut-off from 0 (present value) to something more like 20 to 30. This eliminates surface in-water volume scattering returns that are not related to the surface waves.

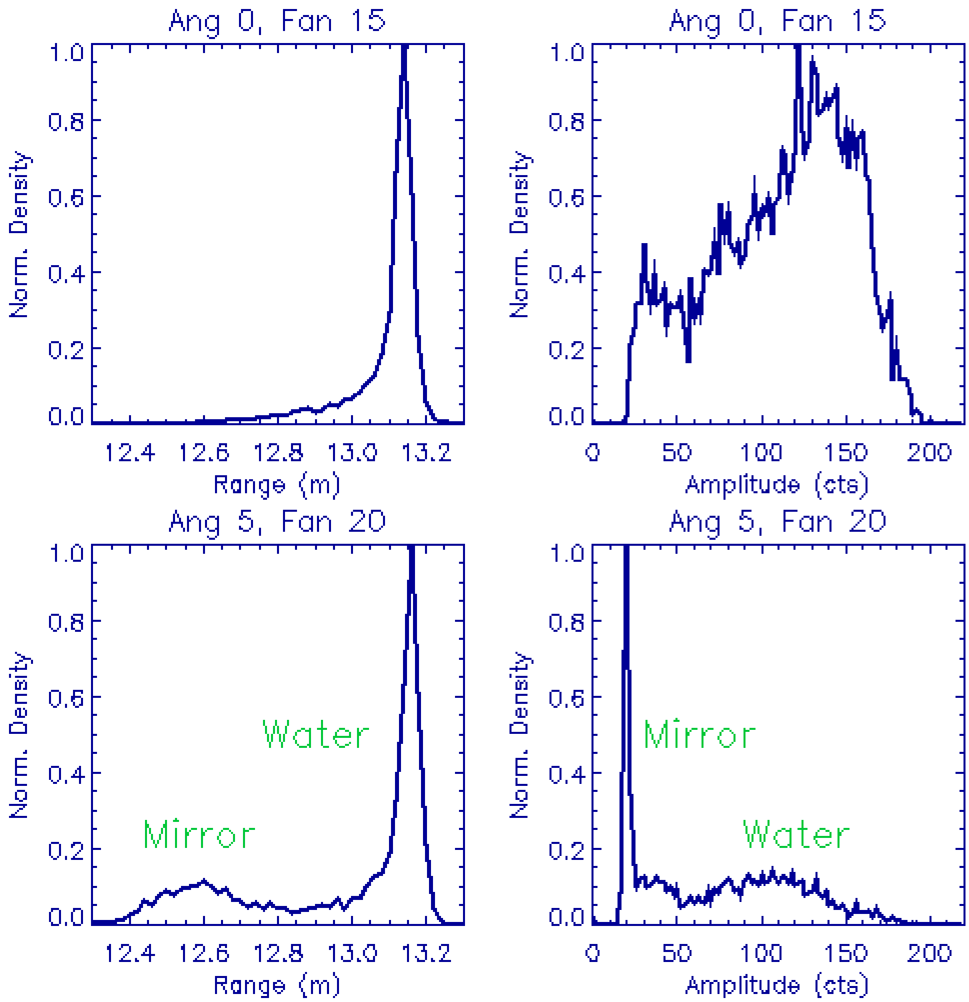



**Figure 14** Sample laser range and amplitude probability density functions data from the wavetank tests. Top panels are for an incidence angle near to 0 deg., the bottom for an angle of 5 deg. upwind. Note the pronounced bimodal range and power distribution in the bottom case, but also in the upper example. In essence the low range and power cases are associated with the mirror return.

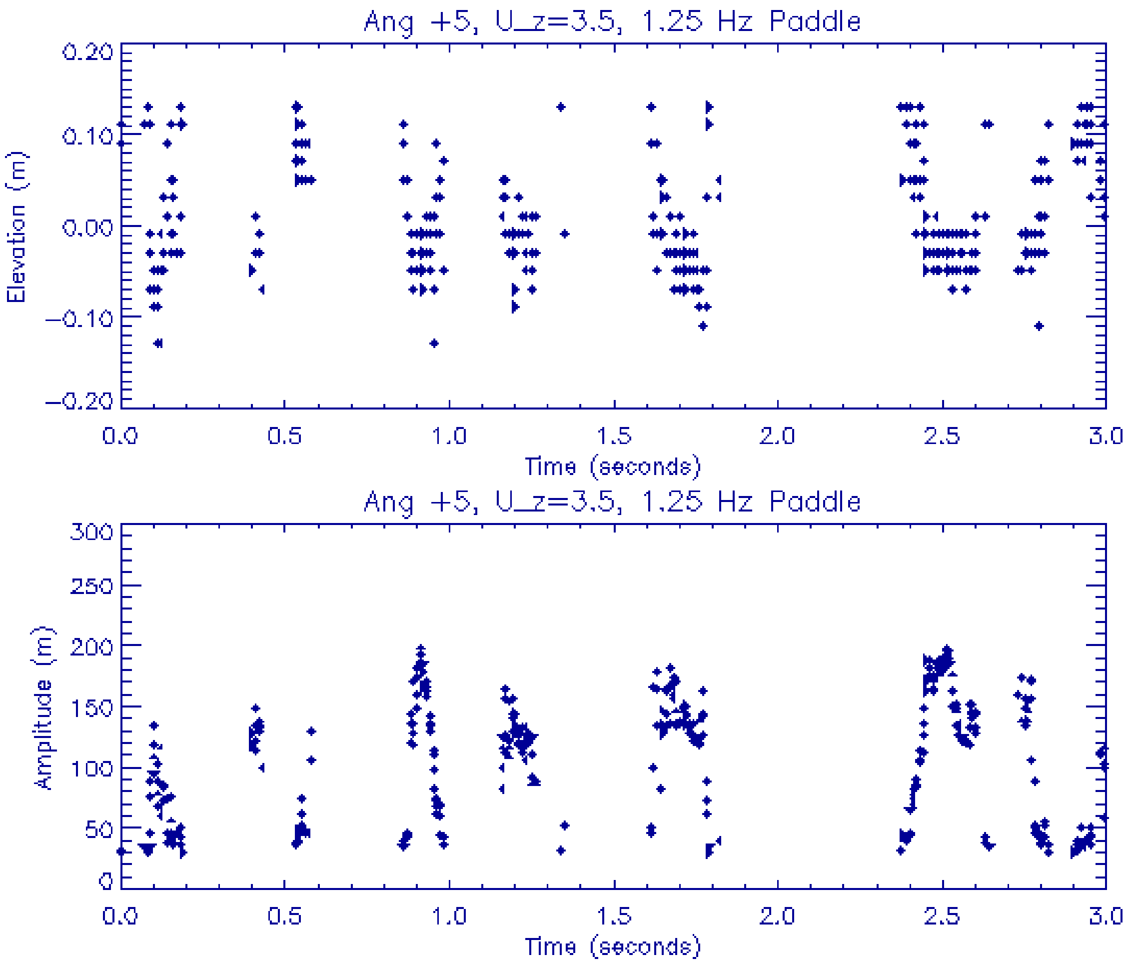



**Figure 15** Sample laser range and amplitude time series for the case when a 1.25 Hz paddle wave is generated along with a 3 m/s wind. The only data shown are those case when the range is well above the 12.4-12.6 mirror return and the laser power is above 25 counts in amplitude. These are the criterion for assuming a specular reflection as discussed in this section. Note that the segments where the laser works are periodic in some relation to the slope of the 1.25 Hz wave (2.5 Hz) where roughness elements are generated along the steepest part of the gravity wave.

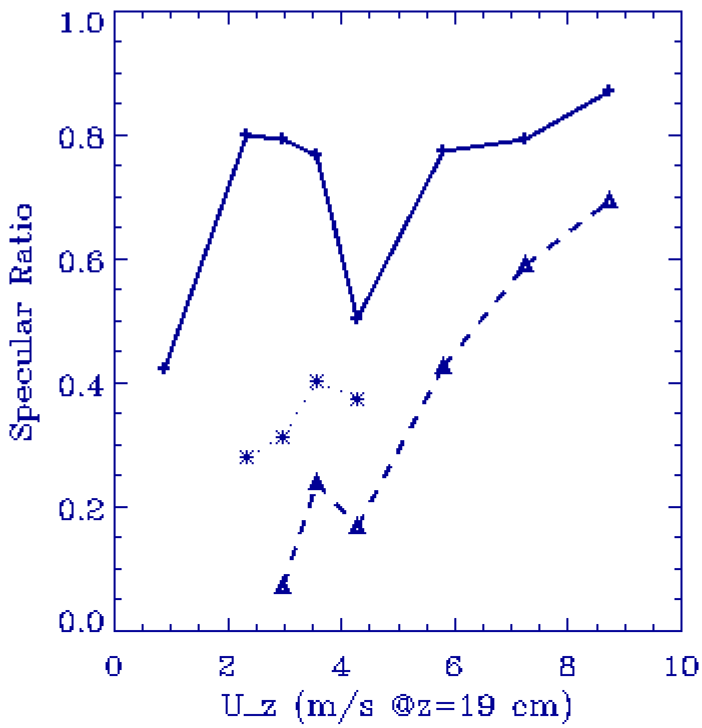



**Figure 16** Variation of the computed specular ratio versus the wind speed for three different upwind incidence angles: upper (0 deg.), middle (5 deg.), and lower (10 deg.).

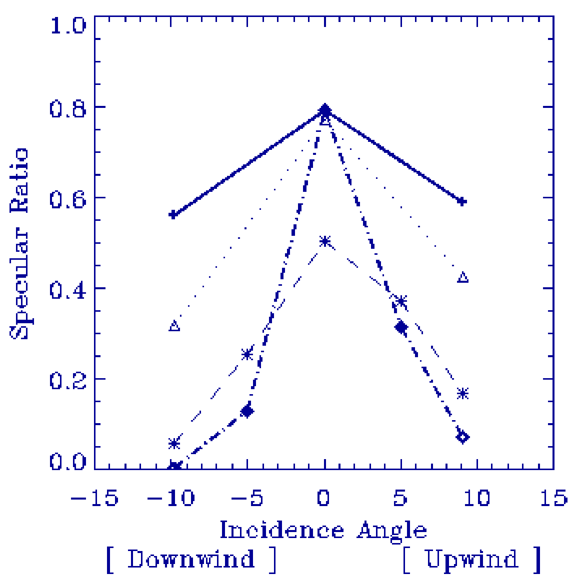



**Figure 17** Variation of the computed specular ratio versus the incidence angle for four different wind speeds (2.8, 4.3, 5.7,7.2 m/s– lower to upper traces).

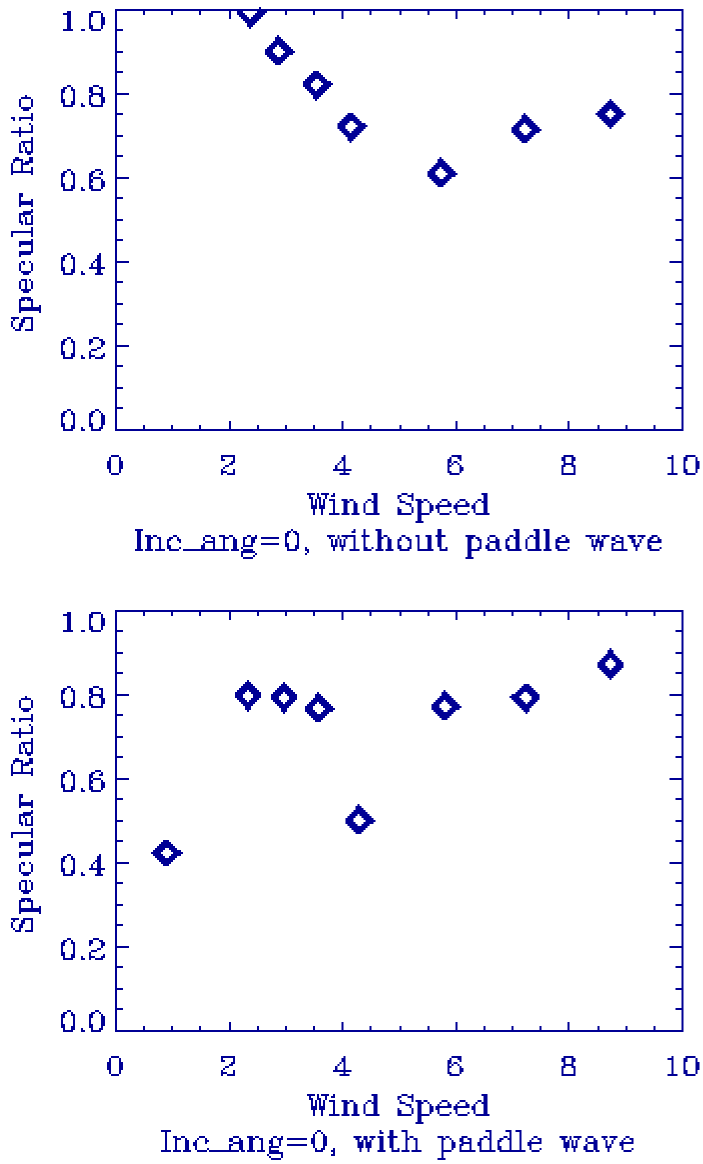



**Figure 18** Variation of the computed specular ratio versus wind speed showing the upwind (+) and downwind (*) data.

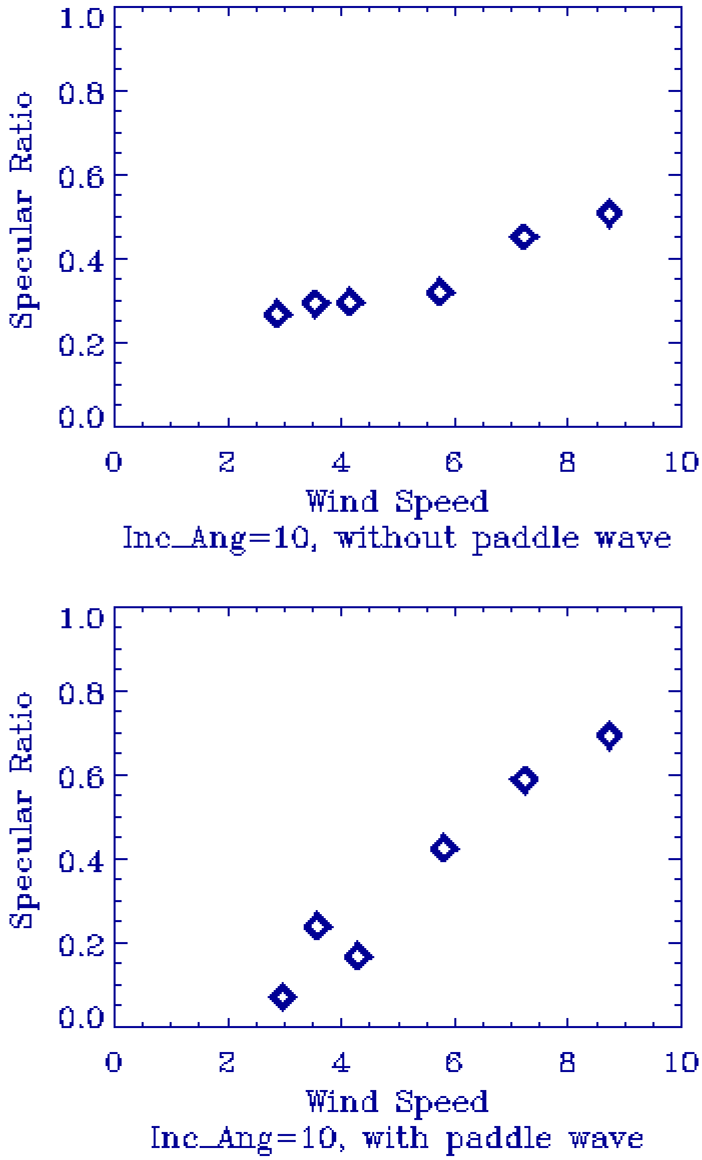



**Figure 19** Variation of the computed specular ratio versus wind speed showing the upwind (+) and downwind (*) data.

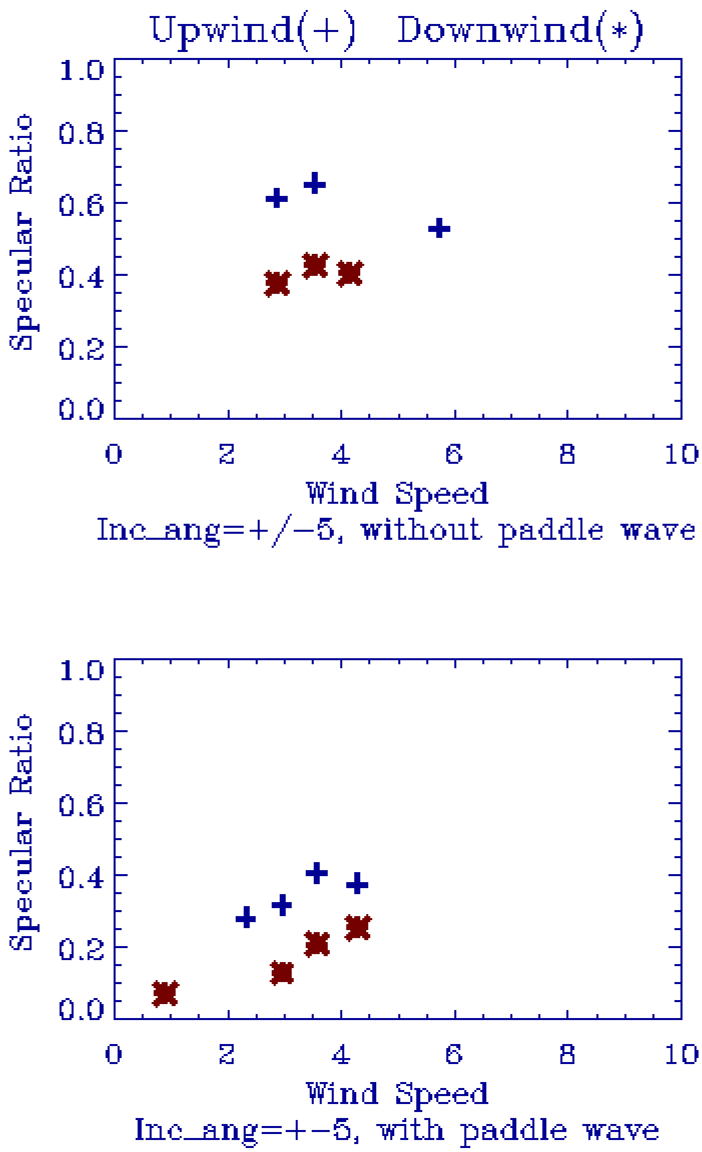



**Figure 20** Variation of the computed specular ratio versus wind speed showing the upwind (+) and downwind (*) data. Data here are for the 5 deg. incidence angles.

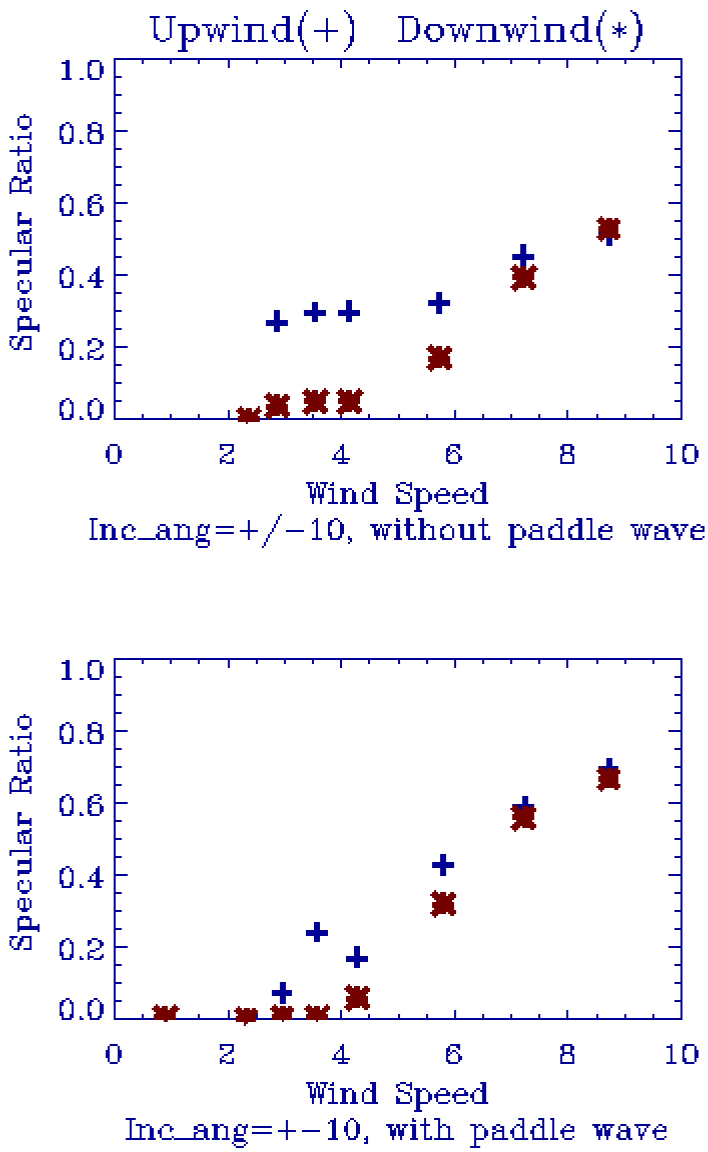



**Figure 21** Variation of the computed specular ratio versus wind speed showing the upwind (+) and downwind (*) data. Data here are for the 10 deg. incidence angles.

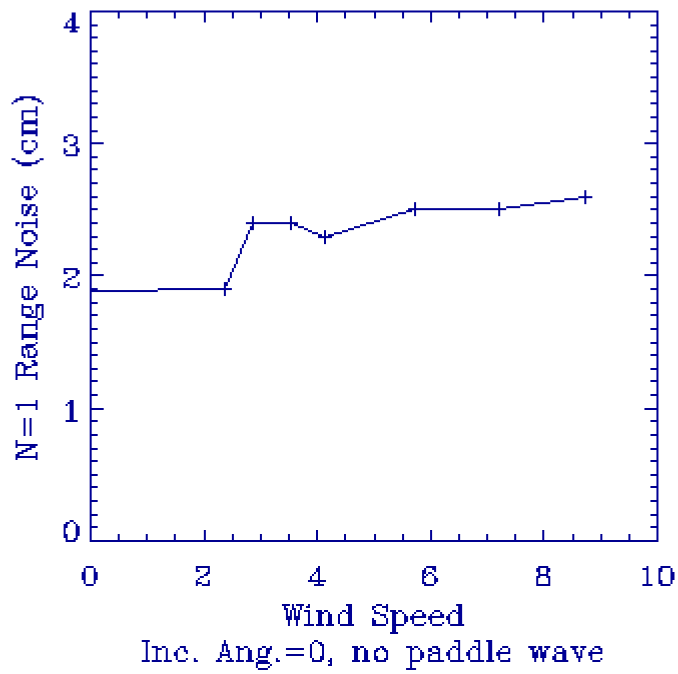



**Figure 22** Computed range noise versus wind speed for the number-to-average set = 1 for the laser altimeter data collection. Note that with 38 pulses to average one can expect something of the order of six reduction in this level.

## 7 Experiment 3: Water surface penetration at 903 nm using the Riegl IR lasers

The objective here was to determine if the near IR laser penetrates water surface and, if so, to characterize this behavior.

In initial tests, the laser was set up in the lab. to range onto a mirror and down into a bucket of water. During these tests, it was noticed that when the water surface was calm the distance measurements appeared to be the coming from the bottom of the bucket rather than from the water surface as was expected based on the general reported behavior of infrared radiation. In looking closer at the problem it was readily apparent that the signal was indeed propagating through the water column of depth as much as 0.5 m. The range measured was due to the diffuse reflection from either the bottom of our plastic bucket or the floor beneath it. We determined that in this case it was the floor by putting an black absorbing target under the bucket

So, what we find is that the IR laser signal can travel through water. If a relatively strongly scattering and diffuse target is located down in the water then the laser will choose to range off this target IF AND ONLY IF the surface reflection is not occurring. This is a rare event on the open-ocean where we seldom see a complete lack of surface reflection signals and there are seldom strong distributed targets under the water.

However, there is a second kind of scattering that does seem to occur in the field and in the lab. that allows the laser to properly range to the surface even in the absence of a surface reflection. What we find (as seen in Fig. 2) is the laser power amplitude data is the indicator of two distinctly different types of returns. The usual specular return power levels vary from say 40 to 180 counts depending on how much of the surface within the laser footprint aligns directly normal to the viewing angle. However, if we remove this possibility and also the floor returns (through our bucket) we are left with the laser ranging but at much lower return power**. In that case the laser now ranged off the water surface again but at a much lower power level of the order of 10 in amplitude. We assumed this to be the initial in-water volume scatter signal as the specular return amplitude is something of the order of 180 counts. Note that this level accords with the field data of Fig. 2 above where there was a bimodal amplitude distribution.**

Having determined that the infrared lasers could penetrate the water surface, we used surface of known power that could be lowered into the water of the wind-wave tank at Wallops Flight Facility. We slowly moved this surface into the tank to determine how far below the water surface the laser could range.

*<u>Laser and experiment set-up descriptions</u>*

The laser was placed at the northern end of the wave tank (above panel 1) and was fired onto a mirror at 12.4 meters down the tank (above panel 9). See section 6 of this report for further detail. The laser was able to reflect off the mirror into the wave tank. The total distance from the laser to the water surface in the wave tank was approximately 13.1 meters. C. Schirtzinger designed and constructed a sand blasted aluminum square (approximately six inches square and 80% reflectivity) which was attached to a 2 m pole at an approximate 10° angle.  This pole was then marked to indicate into 5 cm vertical increments.

*Experiments and results*

Data were collected by ranging off the aluminum plate starting at the surface and continuing into the water stopping to take data at each 5 cm increment until the signal was lost.  We were able to take data sets to approximately 50 cm below the surface before the mirror return began to predominate.  The data sets can be found at G:\longez\riegl\surf_pen.  A1.lsr is the surface data, A2.lsr is the data taken 5 cm beneath the surface; A3.lsr is the data from 10 cm beneath the surface and so forth.  In some instances there are two files for some cases; these files are denoted by an A following the number in the file name.  Also, this document can be found in the same folder and is named Penetration.doc.

As the plate was lowered into the water, the power level decreased.  Figure 23 shows the depth of the aluminum plate in respect to the power level.  It is clear that there was an almost linear decrease versus water depth.   The extrapolated limit of the water depth for this penetration test appears to be about 0.65 m.  We expect that the Riegl amplitude data is coming from a logarithmic converter.  if this is the case then the data is falling off as something like $\exp^{-(A\,d)}$ where d is the depth and A is an attenuation coefficient.  Our conclusion is that we will probably not encounter any cases in the field where we begin to range off the ocean bottom or subsurface ‘targets’ – but something like submerged weeds could be a remote possibility if the specular return off the surface is absent under light winds.

**Figure 23** Laser return power amplitude (in counts) versus the depth of the target under the water surface.